

# Black Hole Accretion in Transient X-Ray Binaries

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Recent work on the modes of accretion onto black holes (BHs) in Soft X-Ray Transients (SXTs) is reviewed, with an emphasis on uncertainties affecting models of accretion during quiescence (inner hot flow, outer thin disk). Various interpretations of the quiescent X-ray luminosity difference between systems containing neutron stars (NSs) and systems containing BH candidates are also summarized. A new scenario, which does not require BH candidates to possess an event horizon, is presented here. This scenario may be ruled out in the future, from detailed X-ray spectroscopic diagnostics or from the absence of type I X-ray bursts in systems containing BH candidates.

## 1 Introduction

One of the main interests for studying accretion in close binary star systems is that we know better in these systems than anywhere else the general conditions under which accretion proceeds (e.g. binary size and geometry, donor and accretor masses, etc...). Many such close binary systems are transient: they semi-regularly experience large amplitude outbursts followed by long periods of quiescence. Depending on the nature of the compact object, these systems are called Dwarf Novae (DN; for a white dwarf accretor; see Warner 1995 for a review) or Soft X-ray Transients (SXTs; for a neutron star or black hole accretor; see Lewin, van Paradijs & van den Heuvel 1995 for a review).

Although this contribution is focused on the nature of accretion in BH SXTs (mostly during quiescence), reference will also be made to NS SXTs and DN. The similarities between these three classes of systems are strong, so that one can hope to learn about the compact object from their subtle differences. In §2, I review the motivation for a two-component accretion flow structure (inner hot flow, outer thin disk) in quiescent BH SXTs. In §3, I discuss various uncertainties affecting models of these two components of the accretion flow. In §4, I review the observational status and theoretical interpretations of the quiescent X-ray luminosity difference between systems containing BHs and those containing NSs. In §5, I present an alternative interpretation of this luminosity difference that does not require BH candidates to possess an event horizon.

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## 2 Accretion Flow Structure

The gas accreted onto compact objects in close binary systems is transferred via Roche-lobe overflow by a main-sequence or sub-giant companion. The large specific angular momentum of the gas naturally leads to the conclusion that a thin accretion disk forms in the system (the gas being allowed to radiatively lose energy much more efficiently than momentum when cooling is efficient; see, e.g., Frank, King & Raine 1992 for a review). The presence of thin accretion disks during outburst in transient close binaries has been observationally confirmed by detailed eclipse maps in DN (Horne 1993) and X-ray spectroscopic diagnostics in SXTs (Tanaka & Shibazaki 1996). The situation in quiescence appears more complicated, however.

According to the Disk Instability Model (DIM), the outbursts of transient close binaries are triggered by a thermal-viscous instability occurring when hydrogen becomes partially ionized somewhere in the disk (Meyer & Meyer-Hofmeister 1981; Cannizzo 1993; Lasota 2001a). Lasota (1996) pointed out that if fully-extended, quiescent disks in SXTs were accurately described by the DIM, accretion onto the compact object should proceed at a rate  $\ll 10^{10} \text{ g s}^{-1}$ , i.e. many orders of magnitude smaller than inferred from X-ray observations. In addition, at such a low rate, a thin accretion disk is not expected to emit a substantial amount of X-rays (Narayan, McClintock & Yi 1996). This has led to the general belief that there cannot be a disk extending all the way down to the compact object in quiescent SXTs, as would be expected in the DIM. Wheeler (1996) also pointed out that the optical light from quiescent BH SXTs (excluding the contribution from the companion star; see Narayan et al. 1996) corresponds to black body temperatures in excess of  $10^4 \text{ K}$ , which is too hot for the neutral disk expected in the DIM. Nonetheless, the presence of a disk in quiescence appears required to explain the double-peaked emission lines observed (e.g. Orosz et al. 1994) and the outbursts experienced by SXTs.

An attractive solution to this problem is to postulate that the thin disk is present only in the outer regions of the accretion flow, while it is replaced by a hot, X-ray emitting flow in the vicinity of the BH. This possibility was first proposed by Narayan et al. (1996) and further developed by Esin, McClintock & Narayan 1997 (see also Narayan 1996; Lasota, Narayan & Yi 1996; Narayan, Barret & McClintock 1997; Hameury et al. 1997). These specific models, in which the inner hot flow is assumed to be an advection-dominated accretion flow (ADAF), have been rather successful at explaining the spectral properties of BH SXTs in various spectral states (Esin et al. 1998).

Strong observational support for the presence of a hot flow in the inner regions of BH SXTs during low-luminosity spectral states exists for the un-

usual BH SXT labeled XTE J1118+480 (see McClintock et al. 2001a for a mass function determination). This system is located high above the Galactic plane, so that for the first time EUV and soft X-ray spectral measurements could be obtained for a BH SXT (given the small extinction to the source; Garcia et al. 2000). These spectroscopic data were obtained as part of an extensive multiwavelength campaign during the low/hard-state outburst that led to the discovery of this system (Hynes et al. 2000; McClintock et al. 2001b and references therein). The low-state spectral energy distribution of XTE J1118+480 strongly suggests the presence of a thermal component peaking at  $\sim 50$  eV, in addition to the hard power law seen at higher energies (McClintock et al. 2001b). As explicitly shown by Esin et al. (2001), these data are best interpreted as indicating that the thin disk in this system (responsible for the thermal emission) is truncated at several tens of Schwarzschild radii from the BH, where it is replaced by a hot accretion flow (responsible for the power law emission observed). It is difficult to interpret the thermal emission observed as power-law emission from a corona that has been reprocessed by a fully extended, underlying disk (because the thermal component is apparently more energetic than the power-law component; Esin et al. 2001).

### 3 Uncertainties

Based on the successful spectral modeling of Esin et al. (1998) and the evidence in XTE J1118+480 (as well as other arguments discussed in §2), there are good reasons to believe that the inner regions of thin disks in quiescent BH SXTs are replaced by hot accretion flows. Many important components of this scenario are poorly constrained, however. A major uncertainty comes from our lack of understanding of the nature of the transition between the two components of the accretion flow. Although several mechanisms for the “evaporation” of the disk into a hot flow have been explored in the literature (Meyer & Meyer-Hofmeister 1994; Honma 1996; de Kool & Wickramasinghe 1999; Rozanska & Czerny 2000; Manmoto & Kato 2000; Spruit & Deufel 2001; Ball, Narayan & Quataert 2001), none of these theories provide reliable predictions that can be put to the observational test. In what follows, the discussion will be focused on additional uncertainties affecting models of the inner hot flow and the outer thin disk separately.

#### 3.1 Inner Hot Flow

The work on hot accretion flows in recent years has focused on self-similar, analytical solutions to the problem of accretion onto a BH (but see also the work by Ichimaru 1977; Rees et al. 1982; Abramowicz et al. 1995).

Narayan & Yi (1994; 1995a,b) derived a self-similar, advection-dominated accretion flow (ADAF) solution in which nearly all the gravitational potential energy released during accretion is advected by the flow rather than efficiently radiated locally by the gas (as is the case for thin disk accretion). This advection property requires preferential viscous heating of the ions over the electrons and a two-temperature structure. The latter is allowed if energy transfer between the ion and electron populations is rather inefficient, as is the case if only Coulomb collisions operate. A detailed analysis of the energetics of turbulence and the various dissipation mechanisms involved in this type of flow suggests that preferential ion heating can be achieved only for significantly sub-equipartition magnetic fields (Gruzinov 1998; Quataert 1998; Quataert & Gruzinov 1999). As initially pointed out by Narayan & Yi, two complications with the ADAF solution are that the flow has a positive Bernoulli energy constant (indicating that the gas may be subject to hydrodynamical outflows because it is technically unbound) and is unstable to convection in the radial direction (while the effects of convection on the ADAF structure are neglected).

Blandford & Begelman (1999) explored further the possibility that the hot flow is subject to outflows. They constructed a family of advection-dominated inflow-outflow solutions (ADIOS) in which mass, energy and angular momentum are gradually lost to an outflow as part of the gas is being accreted. They suggested that solutions with negative Bernoulli energy constant, which can be obtained under strong outflow assumptions, are more viable than the initial ADAF solution (see Abramowicz, Lasota & Igumenshchev 2000 for a different view).

Alternatively, Narayan, Igumenshchev & Abramowicz (2000) and Quataert & Gruzinov (2000) explored the role of convection in determining the structure and properties of the hot flow. These authors proposed a convection-dominated accretion flow (CDAF) solution in which radial convection is postulated to dominate over viscous processes to determine the sign of angular momentum transport in the flow. The properties of CDAFs are quite different from those of ADAFs, in particular the presence of an additional convection-driven, outward energy flux that may be at the origin of an outflow launched from the outer regions of the hot flow. An interesting feature of the CDAF solution is that it does not require preferential ion heating like the ADAF solution does (Quataert & Narayan 1999; Ball et al. 2001).

While the temperature structure of ADAFs, ADIOS and CDAFs is close to virial in all three cases, their density structure vary widely:  $\rho \propto R^{-3/2}$  in an ADAF,  $\rho \propto R^{-1/2}$  in a CDAF and a  $\rho$  profile that depends on the wind parameters in an ADIOS. Given an accretion geometry and an accretion rate at which the truncated disk feeds the hot flow in a quiescent BH SXT, the

X-ray emission properties will therefore be largely different depending on the exact nature of the hot flow. The ADAF solution may not be favored because of the neglect of radial convection, the apparent susceptibility to hydrodynamical outflows and the possible difficulty to preferentially heat ions. It is unclear, however, whether the hot flow in quiescent BH SXTs should have an ADIOS-like structure, a CDAF-like structure or none of the above.

Given this uncertain situation, the interest for numerical investigations of the structure of radiatively inefficient hot flows has grown considerably during the last few years. A large number of 2D and 3D hydrodynamical simulations (Igumenshchev, Chen & Abramowicz 1996; Igumenshchev & Abramowicz 1999; 2000; Stone; Pringle & Begelman 1999; Igumenshchev, Abramowicz & Narayan 2000) have indicated that hot flows with a small value of the viscosity parameter  $\alpha$  ( $< 0.1$  or so) are subject to large-scale convective motions (in better agreement with CDAF theory), while hot flows with a large  $\alpha$  value ( $> 0.1$  or so) are subject to strong outflows (in better agreement with ADIOS theory). An obvious shortcoming of all these studies is that an ad-hoc Shakura-Sunyaev-type viscosity has to be included in the Navier-Stokes equations solved to mimic the “viscous” interactions that are thought to be in fact of magnetic origin in this hot plasma (Balbus & Hawley 1991; 1998).

Results of global 3D magneto-hydrodynamical (MHD) numerical simulations of hot flows have appeared only very recently because of the large numerical power required. Hawley, Balbus & Stone (2001) present such a calculation, with strong outflow properties. In addition, these authors argue that treating convection in the hot flow separately from angular momentum transport, as is done in CDAF analytical theories, is incorrect. On the other hand, Igumenshchev & Narayan (2001) present a 3D MHD numerical simulation of hot, spherical accretion (gas with zero net angular momentum) in which convective motions play an important role. The apparent discrepancy between these results may be caused by differences in the physical problems addressed or perhaps different numerical implementations (e.g. allowing or not for explicit magnetic energy dissipation in the equations solved), but it is clear at this point that no consensus has emerged on the structure and properties to expect for hot flows. Additional numerical simulations will likely resolve this issue in the future.

### 3.2 *Outer Thin Disk*

The structure and properties of outer thin disks in quiescent BH SXTs are also subject to considerable uncertainties, mostly because of our ignorance of the nature of viscosity in this case. These uncertainties are large enough that we

are currently unable to predict the rate at which the disk feeds the inner hot flow in these systems (given a mass transfer rate). Although the DIM makes definite predictions for the accretion rate as a function of radius to expect in a quiescent disk ( $\dot{M} \propto R^{2.5}$  or so), the assumption that the bulk of the disk accretes mass with a uniform efficiency of angular momentum transport (expressed as a constant value  $\alpha$  parameter in the DIM) may not be valid.

While the transport in ionized disks during outburst is probably due to MHD turbulence resulting from the non-linear development of the Magneto-Rotational Instability (MRI; Balbus & Hawley 1991; 1998), Gammie & Menou (1998) pointed out that quiescent disks are so neutral that resistive diffusion is important and MHD turbulence may not be sustained during this phase. Menou (2000) reaffirmed by using the MHD numerical simulations of resistive disks of Fleming, Stone & Hawley (2000) in more detailed calculations.

Recently, however, Wardle (1999) and Balbus & Terquem (2001) pointed out that the role of Hall terms had generally been ignored in studies of weakly-ionized disks. Although Hall terms are strongest in low-density environments (hence the discussion for T-Tauri disks), they are not negligibly small in the quiescent disks of close binary systems. Using the scaling derived by Balbus & Terquem (2001; their Eq. 25) and assuming a reasonable sub-equipartition magnetic field, one finds that the resistive diffusion term dominates over Hall effects for typical densities  $\sim 10^{-6} \text{ g cm}^{-3}$  found in quiescent disks. Nonetheless, Hall terms constitute an additional non-ideal MHD effect that will have to be included in future discussions of the level of MHD turbulence to expect in quiescent disks in transient close binaries.<sup>b</sup>

Menou (2000) argued that, in the absence of transport by MHD turbulence during quiescence, another “viscosity” mechanism could then drive accretion (perhaps spiral density waves induced in the disk via tidal interaction with the companion star; Spruit 1987). Even in the absence of an alternative viscosity mechanism operating during quiescence, it is still possible for accretion to proceed via MHD-turbulent, X-ray ionized layers at the disk surface. This layered-accretion scenario, first considered by Gammie (1996) for T-Tauri disks (ionized by cosmic rays), has been discussed in detail by Menou (2001) for quiescent disks in DN. The feasibility of layered accretion has been numerically demonstrated by Fleming & Stone (2002).

It is unclear, however, how relevant the layered accretion model is for quiescent disks in SXTs, because the origin and geometry of the ionizing X-rays are not well understood in these systems (for instance, the low-level of X-ray emission in quiescent BH SXTs may not allow the surface layers to be suffi-

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<sup>b</sup>Balbus & Terquem note how difficult it is to analytically predict the influence of Hall terms because of their potentially stabilizing *and* destabilizing effects.

ciently ionized for MHD turbulence to operate). Nevertheless, the possibility that accretion proceeds via surface layers in quiescent DN rather than in the bulk of the disk as assumed in the DIM shows that our ignorance of the nature of viscosity in quiescent disks results in large uncertainties on the structure and properties of these disks. In particular, layered accretion predicts  $\dot{M} \propto R$  in quiescent disks, as compared to  $\dot{M} \propto R^{2.5}$  or so for the DIM (Menou 2001). Therefore, the rate at which the quiescent disk feeds the hot flow in BH SXTs is currently unpredictable. This situation is unlikely to change until we better understand the mechanism responsible for accretion in quiescent disks.

#### 4 Black Hole – Neutron Star Luminosity Difference

One of the most interesting properties of BH SXTs is their X-ray faintness during quiescence, as compared to NS SXTs. The existence of this difference was first pointed out by Narayan, Garcia & McClintock (1997) and Garcia et al. (1997), when they compared systems experiencing type I X-ray bursts (hence containing NSs) to those with mass functions in excess of  $2-3M_{\odot}$  (presumably containing BHs). Recent deep *Chandra* observations allowed the detection of several faint quiescent BH SXTs, thus confirming with better statistics that quiescent BH systems are about 2 orders of magnitude fainter than their NS equivalents (see Garcia et al. 2001 for the latest data). Since the discovery of this luminosity difference, various interpretations of the observational data have been proposed and debated, as described below.

##### 4.1 Accretion Scenarios

Narayan et al. (1997) interpreted the data on quiescent SXTs as evidence for event horizons in systems containing BH candidates. Indeed, assuming that accretion proceeds via an ADAF in the inner regions of quiescent BH SXTs (§2), a large fraction of the gravitational potential energy released during the accretion process may be stored as thermal energy in the flow and lost through the BH event horizon (thus leading to a very small radiative efficiency). On the contrary, independent of the structure of the accretion flow, one would expect a large radiative efficiency ( $\sim 10-20\%$ ) in quiescent NS SXTs, from the necessity to radiate all the energy released by accretion at the stellar surface. Assuming that accretion proceeds at roughly the same rate in the two classes of systems, one therefore expects quiescent BH SXTs to be less luminous than their NS equivalents.

Menou et al. (1999) attempted to quantify the luminosity difference expected in this accretion scenario with more detailed models. They pointed out the importance of comparing systems with similar orbital periods, to guarantee

comparable mass transfer rates and (presumably) mass accretion rates (allowing a meaningful test). They also showed that quiescent NS SXTs are much less luminous than naively expected, in that only a small fraction ( $\sim 10^{-3}$ ) of the mass transferred must actually reach the NS surface. This could be achieved via the action of an efficient “propeller effect” in these systems (see also Asai et al. 1998). Menou & McClintock (2001) attempted to further test the ADAF+propeller scenario for quiescent NS SXTs, by using multiwavelength spectral data available for the specific system Cen X-4. This was not very successful in that the data do not show any signature of the presence of an ADAF in this system. Chandler & Rutledge (2000) further questioned the validity of the propeller picture by showing the near absence of X-ray pulsations when the NS SXT Aql X-1 fades into quiescence, while it is supposed to enter the propeller regime at that point.

Recently, Loeb, Narayan & Raymond (2001) and Abramowicz & Igumenshchev (2001) suggested that the observed X-ray luminosity difference of a factor  $\sim 100$  would be better understood if one accounts for the modified hot flow structure expected from strong convection (CDAF theory). It is unclear how reliable these interpretations are, however, because of various oversimplifications (e.g. neglect of the stellar magnetic field, unproven relevance of CDAF theory for the case of accretion onto a compact object with a hard surface; see also discussion in Lasota 2001b). The current situation with accretion scenarios for quiescent BH and NS SXTs largely reflects the numerous uncertainties associated with hot flow models, as discussed in §3.

#### 4.2 *Stellar Scenarios*

Bildsten & Rutledge (2000) proposed that the quiescent X-ray emission of BH SXTs is dominated by coronal emission from the rapidly-rotating companion star in these systems. This possibility has been challenged by Lasota (2000) and cannot explain the excessive X-ray emission in at least two known quiescent BH SXTs (GRO J0422+32 and V404 Cyg; see Bildsten & Rutledge 2000; Narayan, Garcia & McClintock 2001). X-ray spectral diagnostics also challenge this scenario in several additional systems (Kong et al. 2001).

Brown, Bildsten & Rutledge (1998) pointed out that the (soft) X-ray emission of quiescent NS SXTs could be powered by NS thermal cooling, following heating by deep crustal compression during outburst. The X-ray luminosities of  $\sim 10^{32} - 10^{33} \text{ erg s}^{-1}$  obtained by Brown et al. (1998), in agreement with the observed values, were later confirmed in more detailed calculations by Colpi et al. (2001; see also Ushomirsky & Rutledge 2001). The unusually low quiescent X-ray luminosity of the ms X-ray pulsar SAX J1808-36 (Wijnands

et al. 2001a) was expected in this scenario given the outburst properties of this system (Brown et al. 1998). The NS cooling interpretation is further supported by detailed NS hydrogen atmosphere fits to the X-ray data which require an emission region of size comparable to the entire NS surface, as expected (Rutledge et al. 1999; 2000; 2001a,b). These atmosphere models are successful in fitting the soft X-ray spectra of several sources recently discovered in globular clusters as well (Rutledge et al. 2001c; Grindlay et al. 2001). The crustal heating scenario may also be able to explain the case of the NS in the SXT KS 1731-260, despite the unusual outburst and cooling properties of this system (Wijnands et al. 2001b; Rutledge et al. 2001d).

Despite successes, the crustal heating scenario is not without difficulties. The power law component seen in the X-ray spectra of several quiescent NS SXTs (Asai et al. 1996; Campana et al. 1998, Rutledge et al. 2001a,b) is not explained by this scenario and therefore requires a different origin. It is puzzling that in both Aql X-1 and Cen X-4, the thermal and power law components have comparable luminosities, while they should be unrelated according to the crustal heating scenario. This coincidence may be more easily explained in an accretion scenario (which is not incompatible with hydrogen-atmosphere-type emission).

Variability properties of quiescent NS SXTs may also challenge the crustal heating model. Rutledge et al. (2001a) attributed the long-term variability of Cen X-4 during quiescence to a variation in the power-law component only. Campana et al. (1997) reported significant variability of the quiescent X-ray emission of Cen X-4 (over a period of several days), but it is unclear whether this variability can be simply attributed to the contribution of the power law component in the ROSAT-HRI soft X-ray band. Ushomirsky & Rutledge (2001) suggest that transient accretion events could lead to specific variability patterns of the NS thermal emission in the crustal heating scenario. Nonetheless, Rutledge et al. (2001b) acknowledge that the long-term variability of the thermal component that they observed in Aql X-1 during quiescence is not easily explained by the crustal heating scenario.

### 4.3 *Other Scenarios*

Other interpretations of the X-ray emission from quiescent SXTs have been proposed, including the radio-pulsar interpretation of Campana & Stella (2000) for NS SXTs. These alternatives are critically reviewed by Narayan et al. (2001).

## 5 Evidence for Event Horizons?

Whether the quiescent X-ray emission of SXTs is powered by accretion or NS cooling, the scenarios discussed in the previous section attribute, directly or indirectly, the faintness of quiescent BH SXTs to the lack of a hard surface in these systems.<sup>c</sup> The observed luminosity difference has therefore been interpreted as evidence for event horizons in systems containing BH candidates.

This argument is constructed by elimination: to establish the presence of event horizons in systems containing BH candidates, one should eliminate the possibility of an exotic compact object with a hard surface and a mass in excess of  $2-3M_{\odot}$  (the usual general relativity limit for a NS, beyond which collapse to a BH is traditionally unavoidable; Rhoades & Ruffini 1974; Kalogera & Baym 1996). In this section, a specific scenario which makes this exotic assumption is considered in more detail (systems containing BH candidates are still referred to as BH SXTs, for simplicity).

Assuming that the quiescent X-ray emission of SXTs is powered by accretion,<sup>d</sup> the radiative efficiency should be comparable in BH and NS SXTs (say  $\sim 10\%$ ), if hard surfaces are present in both cases, because the compact objects should have comparable compactness in first approximation (see below). Is it possible for accretion to proceed at a rate  $\sim 100$  times smaller in BH SXTs during quiescence (only because of their  $\sim 5$  times more massive compact objects) and thus explain the observed luminosity difference? As emphasized by Menou et al. (1999), the mass transfer rates in BH and NS SXTs should be comparable, as long as one compares systems with similar orbital periods. In addition, a close inspection of the scaling with central mass of the accretion rate in quiescent disks, in both the DIM and the layered accretion model of Menou (2001), reveals only a weak dependence on the mass of the central object, that is insufficient to explain the observed luminosity difference. One is therefore tempted to focus on differences in the properties of the flow in the vicinity of the compact object to explain the observed luminosity difference.

### 5.1 Accretion vs. Spindown Luminosity

It is natural to expect BH candidates, even with a hard surface, to be more compact than NSs, because of their larger masses. It is then possible for NSs radii to exceed the radius of the marginally stable orbit for an object

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<sup>c</sup>As an exception, if the quiescent X-ray emission of NS SXTs is powered by NS cooling while coronal activity dominates in quiescent BH SXTs, the lack of hard surface in BH SXTs is not crucial (but see objections to the coronal emission scenario in §4.2).

<sup>d</sup>The specific scenario considered here does not exclude an additional contribution from NS cooling to the X-ray emission of quiescent NS SXTs.

of their mass, while BH candidates, being more compact, could lie within their marginally stable orbit (currently favored NS equations of state allow for NS radii both smaller and larger than the corresponding marginally stable orbit radius; e.g. Kalogera & Baym 1996). Based on this difference between BH candidates and NSs, an accretion scenario can be constructed in which the quiescent X-ray luminosity difference is explained without requiring BH candidates to have an event horizon.

For compact enough BH candidates, accretion will be transsonic and transalfvenic because the flow radial speed approaches the speed of light as the compact object radius approaches a Schwarzschild radius. In this case, the gas reaching the BH candidate surface is viscously disconnected from the rest of the flow and, independently of the flow structure at large radii, emission from the gas shocking the surface should have a radiative efficiency  $\sim 10\%$  or so. This implies very low accretion rates,  $\sim 10^{10-11} \text{ g s}^{-1}$ , in quiescent BH SXTs.

It is reasonable to expect similar mass accretion rates in BH and NS SXTs during quiescence (see point above). In the case of NS accretion, however, if the NS radius exceeds the marginally stable orbit, the entire flow is viscously connected. Medvedev & Narayan (2001) have shown that the flow can adopt a hot configuration in this case, through which it effectively spins down the NS. Medvedev & Narayan (2001) note that the spindown luminosity dominates over the accretion luminosity for low enough accretion rates. In particular, for accretion rates  $\sim 10^{10-11} \text{ g s}^{-1}$ , as discussed above, and NS spin frequencies  $\sim 300 \text{ Hz}$  (a reasonable value for NSs in SXTs; e.g., Wijnands & van der Klis 1998; White & Zhang 1997), a spindown luminosity of  $\sim 10^{33} \text{ erg s}^{-1}$  is expected, much in excess of the corresponding accretion luminosity. This spindown luminosity is right at the level required to explain the quiescent X-ray luminosity of NS SXTs (slight changes in model parameters, such the NS spin rate, can easily account for the range of luminosities observed in quiescent NS SXTs). Thus, in the accretion scenario considered here, quiescent BH SXTs are less luminous than their NS equivalents because, in their case, the flow is viscously disconnected from the compact object and only the accretion luminosity, at a level of  $\sim 10^{30-31} \text{ erg s}^{-1}$ , is liberated (independently of the BH candidate spin rate). Note that the hot settling flow solution of Medvedev & Narayan (2001) is strictly valid only for an unmagnetized NS. One can show that for surface field strengths roughly  $\leq 10^8 \text{ G}$  (as is reasonable for NS in SXTs), an unmagnetized approximation is relevant because the thermal pressure in the hot settling flow dominates over the magnetic field pressure at the stellar surface.

The accretion scenario outlined above is dynamically-consistent with recent work on hot accretion flows and energetically-consistent with the observed

X-ray luminosity difference. It is arbitrary only in that it postulates the existence of massive, very compact objects and it assumes that NSs lie beyond their marginally stable orbits. For simplicity, the issue of thermal emission from the massive compact object in BH SXTs and the role of magnetic fields associated with this object were ignored (the fields could arguably be weak and the object internal structure could be such that crustal heating like in the NS case is not expected).

The value of this scenario may not be as a solid alternative to other interpretations of the observed luminosity difference. Rather, it shows that it could be dangerous to have evidence for BH event horizons rely only on the luminosity difference between BH and NS systems. By using additional observables, however, the evidence will likely be made stronger. Detailed X-ray spectroscopic diagnostics may, for instance, rule out the presence of a hot settling flow in quiescent NS SXTs. Perhaps more importantly, accumulation of mass at the hypothetical surface of the compact object in BH SXTs during outburst may be expected to trigger type I X-ray bursts, by analogy with the NS case (and independently of the detailed internal structure of the hypothetical compact object). The non-detection of these bursts may therefore constitute the strongest evidence for event horizons in BH SXTs. Detailed burst calculations by Heyl & Narayan (2002) for a compact object of arbitrary size support the validity of this test.

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